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David A. Simms
Charles P. Butterfield

Solar Energy Research Institute
1617 Cole Boulevard
Golden, Colorado 80401-3393
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D. A. Simms
C. P. Butterfield

Solar Energy Research Institute
1617 Cole Boulevard
Golden, Colorado 80401

ABSTRACT

The Solar Energy Research Institute's (SERI) Wind Research Program is using Pulse Code Modulation (PCM) telemetry data-acquisition systems to study horizontal-axis wind turbines. Many PCM systems are combined for use in test installations that require accurate measurements from a variety of different locations. SERI has found them ideal for data-acquisition from multiple wind turbines and meteorological towers in wind parks.

A major problem has been in providing the capability to quickly combine and examine incoming data from multiple PCM sources in the field. To solve this problem, SERI has developed a low-cost PC-based PCM telemetry data-reduction system to facilitate quick, in-the-field multiple-channel data analysis. Called the "PC-PCM System," it consists of two basic components. First, PC-compatible hardware boards are used to decode and combine multiple PCM data streams. Up to four hardware boards can be installed in a single PC, which provides the capability to combine data from four PCM streams directly to PC disk or memory. Each stream can have up to 62 data channels. Second, a software package written for use under DOS was developed to simplify data-acquisition control and management. The software provides a quick, easy-to-use interface between the PC and multiple PCM data streams. Called the "Quick-Look Data Management Program," it is a comprehensive menu-driven package used to organize, acquire, process, and display information from incoming PCM data streams.

This paper describes both hardware and software aspects of the SERI PC-PCM system, concentrating on features that make it useful in an experiment test environment to quickly examine and verify incoming data from multiple PCM streams. Also discussed are problems and techniques associated with PC-based telemetry data-acquisition, processing, and real-time display.

INTRODUCTION

PCM-encoded telemetry data systems provide highly accurate measurements over a wide dynamic range with low noise (Strock 1983). These systems are ideal for collecting data related to the study of wind turbines, especially in multiple-turbine wind parks. Typical wind park test installations require multiple-channel measurements taken from a variety of different locations. These can be grouped into three basic categories: turbine rotating, turbine nonrotating, and meteorological.

In the rotating-turbine frame, measurements are made on the turbine blades, blade attachments, and hub. Typical parameters include strain-gauge bending moments and torsion, airfoil surface pressure distributions, total dynamic pressure, and blade pitch angle. These measurements provide data to determine blade aerodynamic and structural loads. In the nonrotating-turbine frame, measurements characterize machine performance and determine turbine loads. This requires data from the turbine nacelle and tower, such as generator power production, tower bending, azimuth and yaw angles, and rotation speed.

To determine characteristics of the wind at a turbine or wind park, meteorological conditions are measured. Anemometers are used to measure near-field horizontal and vertical wind shear. This requires many channels of data on wind speed and wind direction from local upwind anemometer arrays. Atmospheric stability measurements are also important in evaluating characteristics of wind park inflow and outflow. This requires far-field atmospheric boundary layer measurements, including anemometer, temperature, barometric pressure, and dewpoint.

To increase accuracy, simplify installation, and reduce noise, many channels of analog signals are digitized, multiplexed, and encoded into a single PCM stream as close to the measurement source as possible. The stream is then telemetered to a convenient central receiving location and combined with streams from other sources to form a complete digital data set. Streams originating from remote or difficult-to-reach locations can be easily transmitted over a radio-frequency (RF) link. RF links have been especially useful in simplifying data-acquisition from sensors located on rotating wind turbine blades.

SERI's wind program is conducting various field tests in an effort to assist wind industries in the United States to improve reliability and performance of wind turbines. Some current studies include an unsteady aerodynamics experiment (Butterfield 1989, Butterfield and Nelsen 1990), wind park inflow-outflow characterization (Kelley 1989), and advanced airfoil testing (Tangler et al. 1990). A typical test layout is shown in Figure 1. Multichannel hub-mounted rotor packages facilitate rotating-frame measurements from multiple turbines.

SERI has been using PCM systems for many years, bearing their high cost to ensure quality data measurements. Given conditioned analog signals, it is relatively inexpensive to encode and multiplex multichannel data into a PCM stream. The expense lies in providing adequate multi-PCM stream data decoding and reduction. In the past, we had two ways to decode PCM data streams. One involved using a portable PCM-decoding test instrument called a D/PAD (Loral Instrumentation 1987) in the field. The other was to use our laboratory-based telemetry data-reduction system (Fairchild Weston 1985). These two systems represent the extremes of PCM data decoding capability. Neither adequately satisfied our data-processing requirements. What we really needed was a system that combined features of both to provide test engineers in the field with full processing, analysis, and display capabilities for data from multiple PCM streams.

Specifically, we required multiple-stream decoding, derivation of parameters from all channels (across PCM streams), graphic display, data storage, and a means to rapidly update calibration coefficients of many channels. We also needed the ability to monitor long-term meteorological conditions to evaluate test status. These field capabilities are essential because debugging using laboratory-based postprocessing is inefficient and impractical. We could not find a commercial system with these features that could be inexpensively duplicated at our many test sites. We therefore decided to develop our own PC-based PCM system to provide the required field test capabilities. The system consists of PCM-decoding hardware boards (Simms and Butterfield 1990) and a custom Quick-Look PCM data management software program (Simms 1990.) A graphic depiction of data flow through the system is shown is Figure 2.

VP-G07317-01

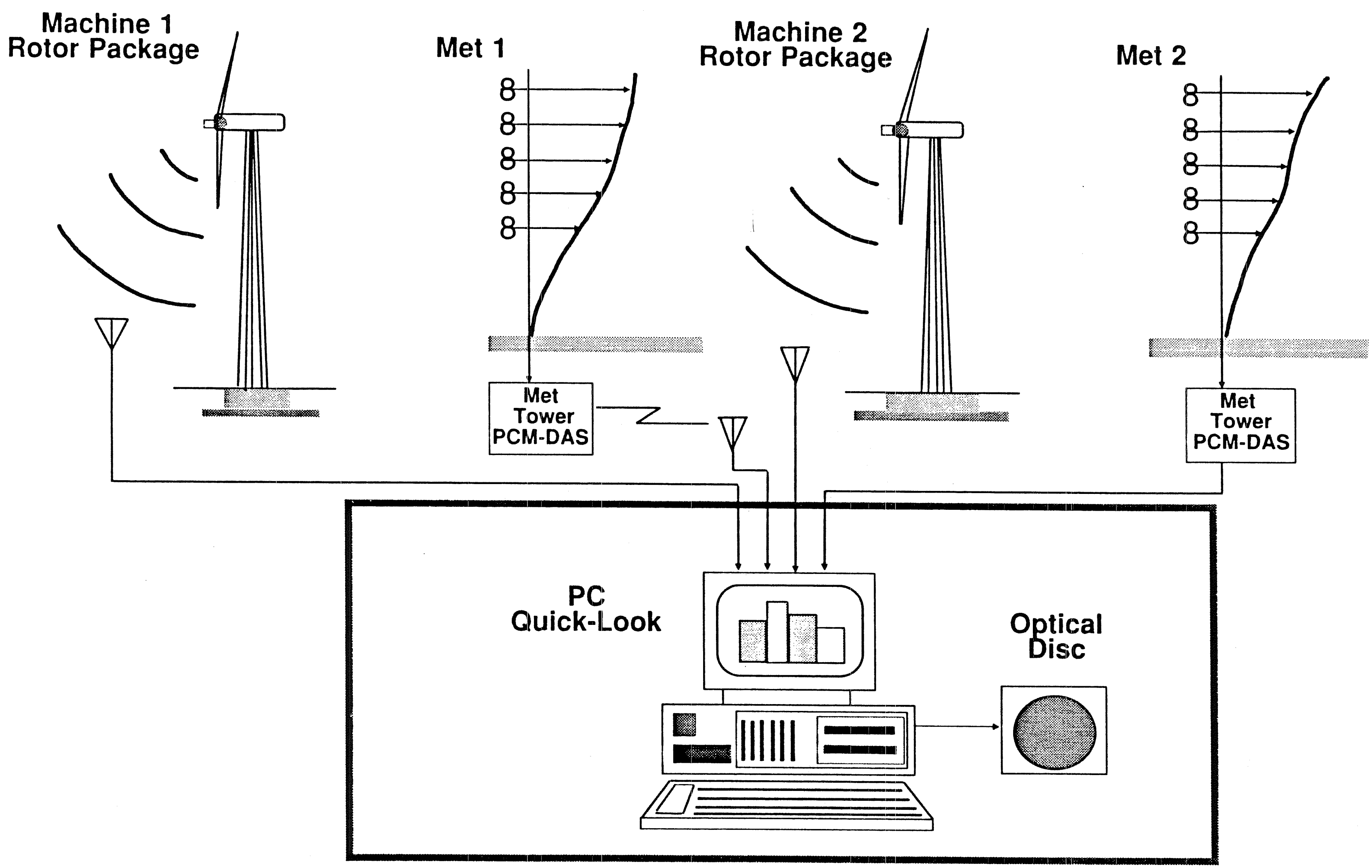

Figure 1. Wind farm multiple-machine/met tower PCM

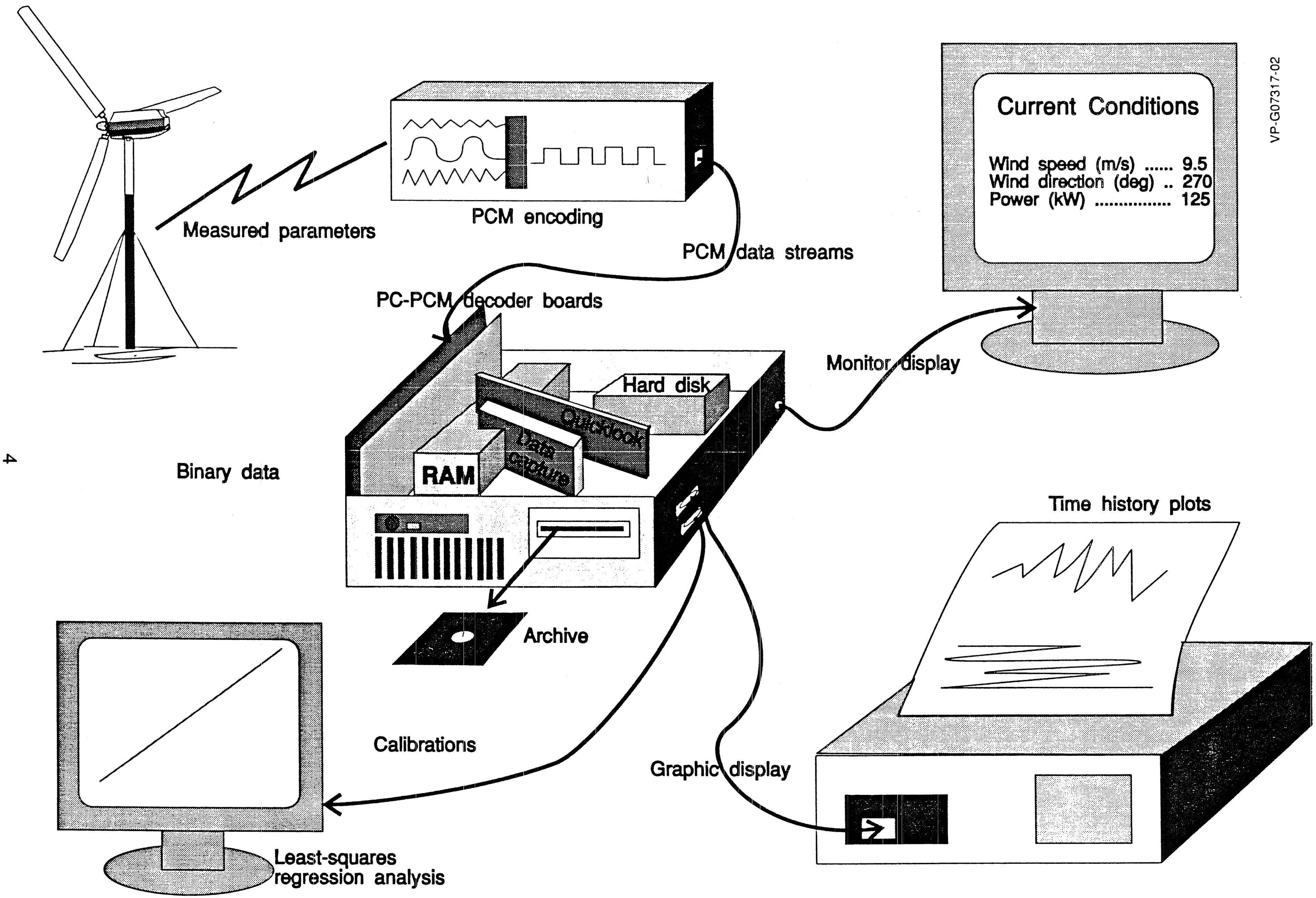

Figure 2. Quick-Look program data flow

INTERFACING A PC TO PCM DATA STREAMS

The main function of the PC-PCM system is to interface a PC with PCM data. This requires some type of PCM-decoding hardware that can transfer data into a PC. Over the past few years in conjunction with a subcontractor, SERI has developed the PC-based PCM-decoding hardware system. This system consists of basic control software and printed circuit boards (APEX Systems Inc. 1988) that fit directly inside the chassis of a PC/AT or compatible computer. PCM data are decoded on the board and transferred to PC memory or disk. One board can decode one PCM stream at a time. Up to four boards can be installed in a PC, permitting data from four streams to be simultaneously combined. The PC-PCM decoder board specifications are summarized in Table I.

Table I. Specifications for PCM Decoder Board

Bit rate	1-800 Kbits/sec
Input streams	4 per board (only one processed at a time)
Input polarity	Negative or positive
Input resistance	> 10 K ohms
Codes	Bi-phase L, NRZ
Bit sync type	Phase locked loop (PLL)
Input data format	8-12 bits/word, MSB first
Words per frame	2-64 (including sync)
Sync words per frame	1-3 (maximum 32 bits)

In conjunction with the PCM decoder boards, we also developed an analog interface module which reconstructs analog output from up to eight channels per stream. The basic intent was to enable test engineers to use real-time analog test instruments such as a spectrum analyzer or chart recorder. The analog module is an optional part of the system. Specifications are shown in Table II.

Table II. Specifications for Analog Interface Module

Analog outputs	8 channels (user selectable via thumbwheels)
Output polarity	Unipolar or bipolar
Output range	0 to 10V, 0 to 20V, -5 to 5V, -10 to 10V
PCM inputs	4 (only one processed at a time)
Status lights	PLL lock, frame sync, FIFO, disabled

A full complement of four boards in a PC allows the Quick-Look program to manage data from up to 16 PCM streams. Each board has four inputs and can be quickly reconfigured to cycle through the inputs to grab-sample data from different PCM streams. Various combinations of cyclic or concurrent acquisition can be used. Maximum data-collection rates vary depending on hardware limitations and other variables discussed in following sections.

The PC-PCM boards support standard-format Inter-Range Instrumentation Group (IRIG)-compatible PCM streams with bit rates in the range of 1000 to 800,000 bits/sec, and a maximum of 64 data words (including sync) per frame. Assuming 12-bit data resolution, channel sample rates from 1.3 to 33,000 Hz are possible. Decoding subcommutated or supermultiplexed PCM data is not currently supported.

During acquisition of PCM data, all values are digital raw "counts" derived from binary data words that have been decoded from the PCM data streams. Data resolution is determined by the number of bits used to represent each measured data value. We typically use 12-bit resolution, which is 1 part in 2^{12}, corresponding to count values ranging from 0 to 4095. The Quick-Look program interprets the raw count values provided by the PCM decoding hardware and converts them to engineering units using calibration coefficients from its data-base.

OVERVIEW OF THE QUICK-LOOK PROGRAM

The Quick-Look program is a comprehensive software package designed to manage data from multiple incoming data sources. The major objective in developing the program was to provide a way to quickly examine data from PCM streams in an experiment test environment. Other objectives include on-line channel data-base management, hardware debugging capability, and automated calibration procedures.

Menus are presented to the user enabling quick selection of desired options. Each menu contains a title followed by lines listing current available options. The user moves a highlighted bar to select the desired operation. At that point, another level of menu options may appear or option execution may begin. The main program menu presents the user with options that are summarized in Table III. These options identify all the basic features of the Quick-Look program.

Table III. Quick-Look Program Features

Hardware Set-Up Define all parameters related to interfacing the PC with peripheral PCM decoding devices.
PCM Configuration Data-Base Define and maintain the characteristics of all potential incoming PCM streams.
Channel Data-Base Define and maintain information associated with all measured data channels.
Derived-Parameter Data-Base Establish and organize ancillary derived channel equations.
Acquire Data Select channels, monitor current conditions, collect data and store them in a disk file.
Display Recorded Data Comprehensive graphic or alphanumeric display of previously recorded data sets.
Channel Calibration Generate calibration coefficients using a multiple-channel least-squares linear regression data processor.
File Maintenance Organize and catalog experiment-associated data files and channel data-bases.
Test Event Log Record the sequence of experiment events.

Typical components of PC-based data-acquisition systems common to both the Quick-Look system and most commercial data-acquisition systems are not described here. This report concentrates on the particular capabilities of the Quick-Look program related to quick handling of PCM data in the field and to conducting calibrations. Although this program was developed to allow the PC to be interfaced with PCM data, the capabilities for data management outlined here could be applied to other types of telemetry-based data-handling systems as well.

LIMITATIONS OF PC-BASED DATA-PROCESSING

A basic premise of the Quick-Look program is that the PC cannot process all incoming data in real time. Because of DOS and central processing unit (CPU) limitations, data collection and data-processing are not done at the same time. These tasks could be combined if incoming data rates are sufficiently slow. However, for most of our applications, we have found that the typical PC cannot concurrently do both adequately. If the processes are independent, then the CPU can be fully dedicated to each task separately. This allows access to higher-rate incoming data and provides greater data-processing capability.

To compensate for the limitations imposed by the PC, two techniques can be used to effectively reduce the quantity of incoming data to a manageable level. First, the PCM data streams can be periodically sampled at a controlled rate. This allows the PC's CPU to selectively alternate between acquiring and processing data. Second, data can be contiguously recorded to disk or memory over a given duration of time and then postprocessed. These techniques are described below.

SAMPLED DATA-ACQUISITION

Sampled data-acquisition is used to provide real-time data-monitoring capability. The incoming PCM streams are periodically sampled to acquire small segments of contiguous data. The segments are quickly processed and displayed to show current conditions. The process is continuously repeated. Up to 135 channels from any combination of incoming PCM streams can be displayed. Each representative value for each channel is determined by averaging 1 to 10,000 contiguous samples. The user selects channels for display and defines an appropriate averaging interval.

For example, selected channels would be displayed on the monitor in the following format:

```
201:Anemometer #1 (m/s)....................... 1.067E+01 (2.502E-01)
307:Power Supply (volts)...................... 2.502E+00 (6.745E-02)
402:Bending Moment (N-m)...................... 5.678E+02 (3.456E+01)
  .                                               .
  .                                               .
```

The first digit of the channel number identifies the PCM stream, and the next two digits identify the data word. The mean and standard deviation values continuously change as data monitoring cycles. The monitor display may lag behind real time by a few seconds, depending on number of channels displayed and calculation overhead.

CONTIGUOUS DATA-ACQUISITION

In contiguous data-acquisition, data streams are recorded in real time, with no gaps. Data from up to four streams can be simultaneously acquired to a disk file up to the limit of available disk space. The data blocks are then postprocessed using features of the Quick-Look program.

During contiguous data collection, no other process can run on the computer. After the block of data is acquired, summary statistics are presented on the monitor display. From these, the user can decide whether the data set meets the necessary criteria.

These data-reduction techniques impose restrictions that the user must be aware of, and they may not be appropriate in certain situations. For example, transients may be missed, or aliasing could be introduced. To provide data values representative of existing conditions, the data segments should be stationary time history records (Bendat and Piersol 1980). The Quick-Look program provides many features that allow evaluation of time series data. It is up to the user to ensure that the data segments are sufficiently long and statistically meaningful to produce adequate results.

For most of our Quick-Look requirements, the limits imposed by the PC-based system are not of concern. In typical field experiments, we have found this system to be extremely useful, especially for monitoring current conditions and conducting channel calibrations. With high-rate incoming data, we do not use this system for full data-processing. Usually, we record all PCM data streams independently to provide complete data sets for comprehensive postprocessing using a full laboratory-based PCM data-reduction system (Fairchild Weston 1985).

DATA-BASE OF PCM STREAM CONFIGURATION AND CHANNEL PARAMETERS

The Quick-Look program provides a form into which a set of configuration parameters defining each PCM stream can be input. The parameters are then used to set up decoding hardware to access streams whose channels are requested. Typical configuration parameters are:

1. PCM stream title
2. Number of data words per frame (data channels)
3. Number of sync words per frame
4. Binary sync bit pattern
5. Bit rate in bits/sec
6. PCM data format (Bi-phase L or NRZ)
7. Signal polarity
8. Bits per word
9. Samples to average.

A data-base is kept for each channel of each PCM stream. A maximum of 70 channels per stream is allowed. The data-base consists of a set of user-definable parameters and corresponding data. The following list contains a typical set of useful parameters:

1. Channel description
2. Sensor location
3. Sensor type
4. Sensor ID number
5. Anti-alias filter setting
6. Sample rate
7. Engineering data units
8. Slope (engineering units per count)
9. Offset (engineering units)
10. Range maximum
11. Range minimum
12. Reference channel for calibration
13. Low, zero (mid), and high calibration values
14. Flag to print mean values to a log file
15. Date and time of latest revision.

Parameters 2-6 are available for bookkeeping purposes, and except for comprehensive printouts they are not used elsewhere in the program. Values do not have to be entered in these fields. Parameters 1 and 7-14 are used in various other places in the software. It may be necessary to enter values in these fields depending on the program option selected.

The channel data-base option of the Quick-Look program provides access to these parameters for any channel on any PCM stream. The user is presented with a form on the screen that displays current parameter values, which can easily be updated or modified. If any changes are made, a new version of the data-base file is written and becomes the current version. Parameter 15 is updated automatically if any changes are made in any field.

Previous versions of the channel data-base are retained so that a history of the channel, including calibration coefficients, is available. The program allows previous versions to be easily recovered. This is especially useful for postprocessing raw PCM data recorded on tape, allowing ready access to data values in correct engineering units.

RAPID MULTICHANNEL CALIBRATION CAPABILITY

Only linear engineering-unit conversions are provided, one slope and offset pair for each channel. The slopes and offsets can be input manually into the channel data-base, if known. They also can be generated based on measured data obtained during "calibration runs" and automatically inserted into the channel data-base. It is possible to quickly generate and update calibration coefficients for many channels from many PCM streams simultaneously. There are four options for calibration runs:

1. 3-level high/mid/low calibration data
2. 2-level high/low calibration data
3. 1-level zero calibrations (determines offset only)
4. A function of another "reference" data channel.

For the first two options, PCM count data are collected at the constant calibration levels for a short duration of time and stored in a file. The channel data-base contains a value in engineering units that should coincide with the measured count value at each level. The count data are read from a file and compared to the reference values. A least-squares regression line is generated from which a slope and offset are found, and correlation statistics are calculated.

For the third option, count values corresponding to the channel zero (or any known level) are stored to a file. The data-base zero value is used as a reference, and a new offset is calculated.

For the fourth option, engineering unit data are concurrently measured from a "reference channel" used to generate coefficients for the channels to be calibrated. The relation between the reference channel and the channel to be calibrated is limited to a simple user-defined mathematical function entered in the channel data-base. A least-squares regression line is generated to obtain the relation between the two variables. This allows a "ramp" calibration to be done, in which the data values are distributed over a wide range, as opposed to discrete known levels.

Upon completion of a calibration run, the user is presented with a page of summary regression statistics, other information pertinent to the least-squares fit, and new calibration values. The user can opt to accept or decline the calibration coefficients based on these statistics. He or she can also set up criteria that automate the acceptance process using defined tolerances. For example, the user can identify acceptable ranges of standard error and correlation coefficient. If the regression statistics are within the ranges, calibration coefficients are automatically accepted and inserted in the data-base. This provides a means to quickly calibrate many channels. It has proven very useful in some of our experiments which require frequent rapid calibration of hundreds of data channels.

CONCLUSIONS

In a single PC, the PC-PCM decoding system provides continuous data-acquisition to memory or disk from up to four streams simultaneously. A variety of software packages can subsequently be used to read and process the data.

The full complement of boards in a PC permits data-handling from a maximum of 16 PCM streams containing up to 62 channels each. The boards are IRIG compatible and are designed for use with standard PCM encoders. The data streams can be accessed by cyclic sampling or simultaneous acquisition or both. Maximum acquisition rates and data storage capacity depend on PC hardware.

Optional analog interface modules can be used in conjunction with the PC-PCM decoder boards. These provide digital-to-analog conversion of up to 8 user-selectable channels per PCM stream, or 32 channels total.

The Quick-Look program, a comprehensive software package designed to work with the PC-PCM hardware boards, is used to manage data from multiple incoming PCM data sources. It provides a way to quickly examine field data in an experiment test environment. Program menus allow easy access to options that facilitate organization, acquisition, processing, and display of information from many PCM data streams.

The Quick-Look program presumes that a PC cannot process all incoming data in real time. It compensates for this by using techniques to reduce the quantity of incoming data to a manageable level. The data-reduction techniques impose limitations that the user must be aware of, and they may not be appropriate in certain situations. However, for most of our Quick-Look requirements, the imposed limitations are not of concern.

In our typical field experiments, we have found the Quick-Look program to be extremely beneficial, especially for real-time monitoring and for conducting multichannel calibrations. The ability to grab contiguous time-series data blocks from multiple streams allows access to high-rate phenomena. Graphic review features provide the test engineer with a means to quickly interpret results. Data bases providing histories of channel configurations and calibration coefficients are essential for accurate postprocessing of recorded raw data sets.

Incorporating the PC-PCM system into small portable computers simplifies remote test monitoring of PCM data. The complete system provides field test engineers with the ability to quickly decode and analyze PCM data.

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